



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

**INCREASING ROAD INFRASTRUCTURE CAPACITY  
THROUGH THE USE OF AUTONOMOUS VEHICLES**

by

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December 2016

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**INCREASING ROAD INFRASTRUCTURE CAPACITY THROUGH THE USE  
OF AUTONOMOUS VEHICLES**

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## **ABSTRACT**

Roadway infrastructure is a critical component to U.S. homeland security. Overland transportation affects the national economy, emergency services, defense, and communication systems. This thesis illustrates the capacity increases to roadways enabled by autonomous vehicle technology. Public policy can enhance the adoption rate of autonomous vehicles to maximize the benefit of this emergent technology on the roadway system. A policy analysis provides a comparison of options and outlines regulations that will be needed to ensure the safe adoption of autonomous vehicle technology nationally.

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## **LIST OF ACRONYMS AND ABBREVIATIONS**

CACC	Cooperative Adaptive Cruise Control
CARS	Car Allowance Rebate System
CBCC	Communication Based Longitudinal Control
DOT	U.S. Department of Transportation
HOT	high-occupancy tolling
IBM	International Business Machines Corporation
ISA	Intelligent Speed Adaptation
LIDAR	Laser Detection and Ranging
TRAMAN21	Traffic Management for the 21st Century
V2I	vehicle to infrastructure communication
V2V	vehicle to vehicle communication
V2X	vehicle to vehicle and infrastructure communication

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## EXECUTIVE SUMMARY

Infrastructure is a critical component in U.S. society, playing a pivotal role in economy, security, and social structure. Specifically, the road transportation network in the United States is a vital part of most of what happens across the country. The majority of freight commerce, comprising a major portion of the U.S. economy, moves over roads. Private citizens rely on the road network to access emergency services, to travel to work, and to secure the necessities of life. Various agencies used the national road infrastructure when responding to natural disasters; the military uses the road network for national defense mobilization. This thesis will illustrate that the capacity of the road network in the United States is insufficient for the current and future needs of the nation. Of the many possible solutions to this issue, the use of autonomous vehicles will be the focus of the investigation, specifically how technology can enable vehicles to travel closer together and at higher speeds. Most importantly, innovation in autonomous vehicle will allow the United States to increase the capacity of surface transport without requiring any changes to the existing infrastructure.

Reported in 2012, interstate trucking transported 13.1 million tons of cargo valued at \$11.1 billion.<sup>1</sup> To put this into perspective, those numbers accounted for 67% of the total cargo weight and 64% of the total shipping dollars in the country. By 2040, those numbers are predicted to increase to 18.7 million tons and \$21.4 billion,<sup>2</sup> and those are interstate freight numbers only. If all goods and services moved over roadways are taken into account, including local commerce, the annual dollar amount swells to \$700 billion. In addition to normal commerce, many lifeline infrastructure systems rely on overland freight deliveries for continued operations.

The nation is at or near a threshold in which a major shift is needed, similar to the transcontinental railroad in the 1860s and the interstate highway system initiated in the 1950s. The focus of thesis is on the capabilities provided by the emergent technology

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<sup>1</sup> Ed Strocko et al., “Freight Facts and Figures 2013,” FHWA Freight Management and Operations, 2014, [http://www.ops.fhwa.dot.gov/freight/freight\\_analysis/nat\\_freight\\_stats/docs/13factsfigures](http://www.ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/docs/13factsfigures)

<sup>2</sup> Ibid.

associated with autonomous vehicles. Significant progress has been made in vehicle control and control systems over the past decades. Fully autonomous vehicles are under development by several manufacturers, most notably Google, the technology giant. The vehicles use an array of sensors to scan their surroundings and have a microprocessor that controls all speed, braking, and steering systems autonomously. Eventually, this technology will be augmented with the capability for autonomous vehicles to communicate with the roadway infrastructure and other vehicles. This level of communication will facilitate the platooning of autonomous vehicles in large groups, enabling vehicles to travel closer together and at high speeds while increasing roadway safety. Mathematical modeling presented in this thesis demonstrates that autonomous vehicle platooning can increase the carrying capacity of road infrastructure up to 500%, without the construction of additional driving lanes.

Public policy must be created to aid the adoption of autonomous vehicle technology, so that the maximum benefits of congestion reduction will be attained. Investigation of both positive and negative government incentives relating to autonomous technology adoption conclude that they are less effective than letting market forces drive change. The technology is emerging at a rate in which government subsidies or vehicle use restrictions are not agile enough to encourage adoption. Vehicle manufacturers are incorporating more components of autonomous technology each model year. The responsibility of the policy maker will be to regulate this technology properly and to legislate traffic laws to ensure a safe and seamless integration of these automations into the existing transportation infrastructure.

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# I. INTRODUCTION

## A. RESEARCH QUESTION

Congestion-induced traffic delays result in an annual cost of between \$48 billion and \$124 billion.<sup>1</sup> According to INRIX and the Centre for Economics and Business Research, congestion delays will amount to a staggering \$184 billion by 2030.<sup>2</sup> These costs arise from a neglected road infrastructure that has not kept pace with demand. What can be done about it is the main question facing the United States. The purpose of this thesis is to propose a solution by investigating the following research question: **“How can public policies be formulated so as to increase the capacity of our critical transportation infrastructure through the use of autonomous vehicles?”**

## B. PROBLEM STATEMENT

Infrastructure is a critical component in U.S. society, playing a pivotal role in economy, security, and social structure. Specifically, the road transportation network in the United States is a vital part of most of what happens across the country. The majority of freight commerce, comprising a major portion of the U.S. economy, moves over roads. Private citizens rely on the road network to access emergency services, to travel to work, and to secure the necessities of life. Various agencies used the national road infrastructure when responding to natural disasters; the military uses the road network for national defense mobilization. This thesis will illustrate that the capacity of the road network in the United States is insufficient for the current and future needs of the nation. Of the many possible solutions to this issue, the use of autonomous vehicles will be the focus of the investigation, specifically how technology can enable vehicles to travel closer together and at higher speeds. Most importantly, innovation in autonomous vehicles will

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<sup>1</sup> Richard Arnott and Kenneth Small, “The Economies of Traffic Congestion,” *American Scientist* 82, no. 5 (1994): 446–455.

<sup>2</sup> Federico Guerrini, “Traffic Congestion Costs Americans \$124 Billion a Year, Report Says,” *Forbes*, October 14, 2014, <http://www.forbes.com/sites/federicoguerrini/2014/10/14/traffic-congestion-costs-americans-124-billion-a-year-report-says/#5dc618576252>.

allow the United States to increase the capacity of surface transport without requiring any changes to the existing infrastructure.

## **C. BACKGROUND**

Transportation of goods and services is perhaps the most significant factor contributing to the composition of the global society. Thousands of years ago ancient trade routes allowed not only for the dissemination of material goods but also information and ideas; ultimately, the search for more efficient trade routes led to the colonization of the Western Hemisphere by European powers. Transportation advances facilitated the coast-to-coast expansion of the United States and development of the nation; furthermore, advances in transportation allowed people to live at a distance from where their food was produced, giving rise to densely populated metropolitan areas. Modern urban centers are possible because transportation networks provided for the rapid movement of essential and consumer goods from their places of production to densely populated cities. Whereas in earlier times, this network was based on water or railways, the advent of the internal combustion engine shifted America's transportation network to roadways. These roads transitioned from simple horse-and-coach trails to a more permanent system of designed and maintained roadways. A significant milestone in road transportation was the creation of the Federal Highway Act of 1956. When signed by President Dwight Eisenhower, this act created the system of interstate and defense highways that are common across America today. The road infrastructure in this country correlates with many aspects of society. As of 2014, the Federal Highway Administration reported over 8.8 million lane miles of roadway in the United States,<sup>3</sup> accounting for over three trillion vehicle miles traveled.<sup>4</sup> These numbers include all vehicle traffic, but a significant amount of commerce is dependent on these roads. Reported in 2012, interstate trucking transported 13.1 million tons of cargo valued at \$11.1 billion.<sup>5</sup> To put this number into perspective,

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<sup>3</sup> "Highway Statistics 2014: Public Road Mileage, Lane-Miles, and VMT 1980–2014," last modified March 21, 2016, <http://www.fhwa.dot.gov/policyinformation/statistics/2014/vmt422c.cfm>.

<sup>4</sup> Ibid.

<sup>5</sup> Ed Strocko et al., "Freight Facts and Figures 2013," FHWA Freight Management and Operations, 2014, [http://www.ops.fhwa.dot.gov/freight/freight\\_analysis/nat\\_freight\\_stats/docs/13factsfigures](http://www.ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/docs/13factsfigures).

those numbers accounted for 67% of the total cargo weight and 64% of the total shipping dollars in the country, all of which are transported over roadways.<sup>6</sup> By 2040, those numbers are predicted to increase to 18.7 million tons and \$21.4 billion;<sup>7</sup> and those numbers are only for interstate freight. If all goods and services moved over roadways are taken into account, including local commerce, the annual dollar amount swells to \$700 billion.<sup>8</sup> In addition to normal commerce, many lifeline infrastructure systems rely on overland freight deliveries for continued operations. According to an American Trucking Association report, with as few as three days' worth of shipping interruption, food shortages would appear.<sup>9</sup> Fuel shortages at service stations would occur in one to two days, and the many hospitals that stock medication on a just-in-time schedule would run out of many supplies and medicines in a single day.<sup>10</sup> Even if deteriorating conditions or service disruptions could be dismissed, these road systems currently fail to meet the needs of the country. Although the United States increased roadway lane miles by nearly five percent from 2004 to 2014, doing so fell short of catching up with the percentage increase in roadway usage.<sup>11</sup> In terms of the past 30 years, the lane mileage available in the United States has increased by only 8.9% (from 8,076,149 to 8,801,995 lane miles), whereas the number of vehicle miles traveled has increased by over 76% (from 1.72 trillion to 3.04 trillion miles traveled).<sup>12</sup> This disparity is significant and has consequences.

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<sup>6</sup> Strocko et al., "Freight Facts and Figures 2013."

<sup>7</sup> Ibid.

<sup>8</sup> Richard D. Holcomb, *When Trucks Stop, America Stops* (Arlington, VA: American Trucking Association, 2015), [http://www.trucking.org/ATA\\_Docs/What\\_We\\_Do/Image\\_and\\_Outreach\\_Programs/When\\_Trucks\\_Stop\\_America\\_Stops.pdf](http://www.trucking.org/ATA_Docs/What_We_Do/Image_and_Outreach_Programs/When_Trucks_Stop_America_Stops.pdf).

<sup>9</sup> Ibid.

<sup>10</sup> Ibid.

<sup>11</sup> U.S. Department of Transportation, "Highway Statistics 2014: Public Road Mileage, Lane-Miles, and VMT 1980–2014," last modified March 21, 2016 <http://www.fhwa.dot.gov/policyinformation/statistics/2014/vmt422c.cfm>.

<sup>12</sup> Ibid.

## D. WHY CONGESTION IS IMPORTANT

A workshop report of the National Research Council stated that “[i]t has been estimated that highway congestion costs Americans approximately \$65 billion per year (2005 dollars) and wastes 2.3 billion gallons of gasoline.”<sup>13</sup> By 2030, an estimated 60 million more residents will live in the United States, further taxing this system.<sup>14</sup> Even the layout of the major interstate systems fails to match the current flow of goods in the nation. The highways across the center of the country follow a primarily east–west pattern and do not match the north–south transfer of goods with Canada and Mexico.<sup>15</sup> Congestion impacts urban areas to a greater degree than rural areas, but based on 2015 U.S. Census Bureau estimations, 85% of the U.S. population resides in a metropolitan statistical area.<sup>16</sup> These issues have risen to the level of national strategic priorities. The 2014 *Quadrennial Homeland Security Review* prioritizes the facilitation of the legal flow of people and goods,<sup>17</sup> and the capacity of the road network must be increased to meet this priority. In urban areas, where the traffic congestion is concentrated, additional land for enlarging road networks is unavailable.<sup>18</sup> Transportation is considered a “lifeline” system because it is needed for national productivity, tied to the cost of food and goods, essential to keep the nation competitive in the global market, and directly impacting citizens’ quality of life.<sup>19</sup> Roadways provide the primary access for emergency protective measures, such as police, fire, and ambulance services. While utility services lie typically high above ground or underground, roadways provide service and repair access to all the

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<sup>13</sup> David Nash et al., “Sustainable Critical Infrastructure Systems,” paper presented at Toward Sustainable Critical Infrastructure Systems: Framing the Challenges Workshop Committee, Washington, DC, 2009, 17.

<sup>14</sup> Ibid., 9.

<sup>15</sup> Ibid., 16.

<sup>16</sup> “Population Estimates: Metropolitan and Micropolitan Statistical Areas,” 2015, <http://www.census.gov/popest/data/metro/totals/2015/index.html>.

<sup>17</sup> U.S. Department of Homeland Security, *2014 Quadrennial Homeland Security Review* (Washington, DC: U.S. Department of Homeland Security, 2014), <http://www.dhs.gov/sites/default/files/publications/qhsr/2014-QHSR.pdf>.

<sup>18</sup> “Viewer Call: A Washington DC Man Asks Bud Wright about the Lack of Road Expansion,” C-SPAN video, July 27, 2015, <http://www.c-span.org/video/?c4546093/viewer-call-washington-dc-man-asks-bud-wright-lack-road-expansion>.

<sup>19</sup> Nash et al., “Sustainable Critical Infrastructure Systems,” 8.



nodes of electrical, water, sewer, and communication infrastructures. Commerce is also reliant upon the roadway network, with transportation costs a factor in the pricing of all commodities. The ability to minimize these transportation costs is necessary because the United States faces increasingly competitive markets in Europe, South Asia, and Southeast Asia.

## **E. AUTONOMOUS CAPABILITIES**

The nation is at or near a threshold in which a major shift is needed, similar to the transcontinental railroad in the 1860s and the interstate highway system initiated in the 1950s. The focus of thesis is on the capabilities provided by the emergent technology associated with autonomous vehicles. Significant progress has been made in vehicle control and control systems over the past decades.<sup>20</sup> Cruise control, a system that allows the vehicle to maintain a speed set by the operator, was once a luxury.<sup>21</sup> Now, speed control systems are a standard in almost every vehicle. The current focus on automobile innovation is vehicle headway (gap) control systems,<sup>22</sup> the most significant facet of which is the automatic braking feature,<sup>23</sup> which automatically applies the braking system when a predetermined distance between the vehicle and another object is reached. The vehicle will intervene for a surprised or distracted driver. The other facet of headway control systems emerging is adaptive cruise control, in which the operators predetermine the distance between their vehicle and the conveyance in front of them, and their vehicle will modulate its speed to maintain that distance.<sup>24</sup> In addition to speed and braking systems, vehicle steering is also becoming automated. Some are novelty systems, such as assistance with parallel parking and trailer attachment, but others are more significant.<sup>25</sup>

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<sup>20</sup> Christina Diakaki et al., *Overview and Analysis of Vehicle Automation and Communication Systems from a Motorway Traffic Management Perspective, Traffic Management for the 21st Century* (Crete, Greece: Technical University of Crete, 2014).

<sup>21</sup> Ibid.

<sup>22</sup> Ibid.

<sup>23</sup> Ibid.

<sup>24</sup> Ibid.

<sup>25</sup> Markus Frank, "Ford Active Park Assist: Parallel Parking for Smarties," *MotorTrend Magazine* Online, December 30, 2008, <http://www.motortrend.com/news/ford-active-park-assist/>.

Active automations currently available include lane keeping systems, in which sensors monitor the lane lines and the vehicle's blind spots and will correct the vehicle's steering if the operator lets it drift.<sup>26</sup> Automatic lane changing and lane merging are the next steps in the evolution of active steering technology. All these improvements are related to convenience and safety systems, meant to augment the actions of a human operator. Parallel developments that would remove the human operator from the vehicle are underway.

Fully autonomous vehicles are under development by several manufacturers, most notably Google, the technology giant.<sup>27</sup> The vehicles use an array of sensors to scan their surroundings and have a microprocessor that controls all speed, braking, and steering systems autonomously. With these autonomous vehicles, a three-level communications hierarchy has been proposed by Diakaki et al.<sup>28</sup> The first level is an in-vehicle regime, in which the automation relies strictly upon onboard sensors and computations.<sup>29</sup> Productivity and traffic assistance systems will be improved by the second and third levels of this communications hierarchy.<sup>30</sup> Vehicle-to-vehicle and vehicle-to-infrastructure regimes allow the automation to send and receive information externally. This level of communication will facilitate the platooning of autonomous vehicles in large groups, enabling vehicles to travel closer together and at high speeds while increasing roadway safety.

## **F. ASSUMPTIONS**

Other options could reduce roadway congestion as well. Although the focus of this thesis is on the use of autonomous vehicles to increase roadway capacity, other possibilities will be briefly addressed.

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<sup>26</sup> Jeremy Laukkonen, "What are Lane Departure Warning Systems?" Cartech, updated August 19, 2016, <http://cartech.about.com/od/Safety/a/What-Are-Lane-Departure-Warning-Systems.htm>.

<sup>27</sup> John Markoff, "Google's Next Phase in Driverless Cars: No Steering Wheel or Brake Pedals," *New York Times*, May 28, 2014.

<sup>28</sup> Diakaki et al., *Overview and Analysis of Vehicle Automation and Communication Systems from a Motorway Traffic Management Perspective*, *Traffic Management for the 21st Century*.

<sup>29</sup> Ibid.

<sup>30</sup> Ibid.

Improved public transportation would reduce congestion in urban areas. If commuters used mass transportation, urban road networks would be more available for the commercial transportation of goods, but public transportation is also dependent on large-scale infrastructure improvements to expand. Mass transit works well in some of the most populous cities (New York, Chicago, San Francisco), yet it is less practical in suburban and rural settings. Land is also scarce in many urban areas, so train infrastructure expansion is often difficult. In some places, it carries a stigma, inhibiting ridership; but it may be the best solution after autonomous vehicles.

High speed rail transportation is another of these possibilities. Proponents believe a new network of passenger trains that would travel at speeds of 220 mph would address many of America's transportation needs.<sup>31</sup> The project has been plagued with setbacks and slow progress.<sup>32</sup> High speed rail requires the creation of an entirely new rail infrastructure and will provide transportation only between large hubs. Follow on transportation would require the use of regional trains and public transportation.<sup>33</sup> Congestion created by commuters travelling within a metropolitan area would be unaffected by rail transit.

Congestion pricing is already in effect in many parts of the country. In this process, tolling is implemented or increased on certain lanes while traffic densities are the highest. This process does not increase the efficiency or capacity of the roadways but instead discourages the use of those roads, affecting congestion to some degree; but as urban populations increase, a point will come at which increasing congestion pricing will become impractical.

The final method to alleviate congestion addressed in this paper is to build more capacity through roadway expansion. By building more lane miles in urban areas, vehicles will have more room to travel. While demand has increased, roadway capacity

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<sup>31</sup> "U.S. High Speed Rail Association, 21st Century Transportation for America," accessed, <http://www.ushsr.com/>, accessed July 26, 2016.

<sup>32</sup> Ron Nixon, "\$11 Billion Later, High-Speed Rail is Inching Along," *New York Times*, August 7, 2014.

<sup>33</sup> "U.S. High Speed Rail Association, 21st Century Transportation for America."

has not. The principal shortcoming with this course of action is the limited amount of land to build in urban areas; furthermore, studies on induced demand have shown that increasing the number of lanes on crowded roadways has a negligible effect on overall congestion.<sup>34</sup> Building more roads has led to more traffic.

## **G. HYPOTHESIS**

The hypothesis in this thesis is that the use of autonomous vehicles is a viable means to increase the capacity of America's roadway infrastructure.

## **H. SUMMARY OF METHOD**

To demonstrate the increase in roadway capacity created by the use of autonomous vehicles, a review of two mathematical models designed to describe roadway congestion follows. The first will model congestion based on human driven vehicle, and the second will describe autonomous transportation. Comparison of these models will demonstrate the capacity increase driverless vehicles can provide to the roadway network.

The strategic significance of this research is to identify possible unintended consequences and the need for the creation (or revision) of regulations and policy reflecting codes and standards (i.e., standardized interfaces for an internet of vehicles). This research will provide the basis for an overall policy analysis to illustrate how public policy can best influence the adoption rate of autonomous vehicles to build roadway capacity. Both government and private sector partners will be analyzed in terms of contributions required to establish and maintain this adoption rate.

The audience for this thesis comprises federal, state, and local decision makers involved in transportation planning. Other audiences include policymakers responsible for creating standards and regulations. This thesis may also of value to academic organizations.

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<sup>34</sup> Adam Mann, "What's Up with that: Building Bigger Roads Actually Makes Traffic Worse," Wired Magazine Online, June 17, 2014, <https://www.wired.com/2014/06/wuwt-traffic-induced-demand/>.

## **I. OVERVIEW OF UPCOMING CHAPTERS**

Chapter II contains a review of the literature available on this topic. Chapter III includes mathematical modelling to verify the capacity increases that autonomous vehicles can bring to roadway networks. Chapter IV provides policy options for decision makers to address and encourage adoption of the technology. Recommendations and conclusions appear in Chapter V.

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## **II. LITERATURE REVIEW**

Academic research reviewed for this thesis included advances in vehicle automation, both in individual vehicles and as part of the motorway system. In addition, several mathematical models of traffic congestion important for the policy recommendations in this thesis were investigated. This literature review has been divided into sections covering autonomous vehicle technology, traffic modelling, and autonomous vehicle efficiency. In future literature reviews, current public policy regarding traffic congestion will be investigated.

### **A. AUTONOMOUS VEHICLE TECHNOLOGY**

Lécué et al., who reinforce the issues presented in the background for this thesis in their 2014 lecture, estimate that in the United States, traffic congestion accounts for 5.5 billion hours of delays and 2.9 billion gallons of wasted fuel,<sup>35</sup> which translates into \$121 billion in losses.<sup>36</sup> These losses of time and fuel have quintupled over the past 30 years. The bulk of their report concerned an International Business Machines Corporation (IBM) project in which sensor networks make scalable and consistent predictions of traffic congestion on specific roadways. This information was intended to allow policy makers determine what parts of their transportation systems required action to reduce this congestion. These predictive systems could be useful in the policy analysis in this thesis.

Sule, Gupta, and Desai present a substantial overview of various autonomous systems available for vehicles,<sup>37</sup> including brief descriptions of technologies ranging from antilock braking to automated night vision to self-parking. Their paper provides no useful modeling, but they present plausible assumptions regarding the safety implications of these systems: Autonomous vehicle systems will cause fewer collisions, increase reliability, increase roadway capacity, and reduce congestion. The last two assumptions

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<sup>35</sup> Freddy Lécué et al., “Predicting Severity of Road Traffic Congestion Using Semantic Web Technologies” (lecture, IBM Research, Smarter Cities Technology Centre, Dublin Ireland, 2014).

<sup>36</sup> Ibid.

<sup>37</sup> Sule Shreya, Gupta Kritak, and Desai Viraj, “Autonomous Cars: The Future of Roadways,” *International Journal of Students’ Research in Technology & Management* 2, no. 6 (2015): 203–206.

are critical to this thesis and will be explored using mathematical modelling in Chapter III.

Diakaki et al. created a comprehensive report for the Technical University of Crete. As part of a larger project, Traffic Management for the 21st century (TRAMAN21), an overview and analysis of vehicle automation and communication systems is the first of five deliverables the team has planned.<sup>38</sup> The purpose of their overview and analysis is to investigate the automation and communication systems in use and in development for all roadway vehicles. An understanding of these systems, evaluated for strengths and weaknesses from the perspective of roadway traffic managers, is important to the policy portion of this thesis. The authors explore all technologies, starting with common technologies such as cruise control, in which the vehicle speed is set by a driver and maintained by the vehicle. The paper carries this technology forward to devices like Cooperative Adaptive Cruise Control (CACC) and Communication-Based Longitudinal Control (CBCC), which take a more active role in speed control and lane control. Intelligent Speed Adaptation (ISA) and Highway Pilot (a temporary autopilot used to control all systems at highway speeds) are also in-vehicle systems that can improve traffic safety when travelling at uninterrupted highway speeds. These technologies will constitute the basis for fully autonomous vehicles. Diakaki et al. take time to create taxonomy, categorizing these technologies. Some systems operate within the vehicle only, and others communicate outside it. These cooperative systems are categorized into three groups: vehicle to vehicle (V2V), vehicle to infrastructure (V2I) and vehicle to both (V2X). The most compelling technology for the purpose of this thesis is vehicle platooning, which uses vehicle-to-vehicle communication; it allows a series of vehicles to coordinate traveling by syncing vehicle speed, lane management, and distance between vehicles to travel more efficiently. Under normal conditions and without platooning, a highway can support 2,000–2,200 vehicles per hour per lane at highway speeds.<sup>39</sup> Simulations of platooning autonomous vehicles can increase the capacity to

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<sup>38</sup> Diakaki et al., *Overview and Analysis of Vehicle Automation and Communication Systems from a Motorway Traffic Management Perspective, Traffic Management for the 21st Century*.

<sup>39</sup> Ibid.



4,300 vehicles per hour per lane. The authors cite another research study showing that if all vehicles on a roadway were to platoon using in-vehicle sensors, roadway capacity could be increased 43%.<sup>40</sup> If all vehicles were equipped with vehicle-to-vehicle communications, this efficiency would increase to 273% greater capacity.<sup>41</sup> These assertions will be further explored in this thesis. Finally, this report also highlights some of the challenges of fully autonomous vehicle platooning, such as the need for robust communications to combat signal delays and message loss between vehicles.

## **B. TRAFFIC CONGESTION MODELLING**

Bando et al. of Aichi University in Japan create a very simple model of traffic congestion in their paper.<sup>42</sup> They regard the dynamics of traffic flow as a collective motion problem, in which perturbations in the system create traffic congestion. This model provides a good starting point for analysis in this thesis. They include only the variables of acceleration and distance between vehicles in their modeling. In their system, congestion can be created spontaneously where only acceleration and deceleration are options for a driver. A phase transition induced by the nonlinear effect of dynamic equations of motion cause the congestion.

Verhoef presented a paper describing how to combat traffic congestion using a flexible road tolling system.<sup>43</sup> Verhoef has developed both a static and dynamic model of traffic congestion and present a mathematical solution to “hypercongestion” through road pricing. This model will be useful for evaluation in this thesis.

Ma, Huang, and Jiang have created a mathematic model of traffic congestion that incorporates variables very valuable in understanding traffic patterns. Although congestion can be anecdotally ascribed to traffic accidents, road work, weather

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<sup>40</sup> Patcharinee Tientrakool, Ya-Chi Ho, and Nicholas F. Maxemchuk, “Highway Capacity Benefits from Using Vehicle-to-Vehicle Communication and Sensors for Collision Avoidance,” paper presented at 2011 IEEE Vehicular Technology Conference (VTC Fall), San Francisco, CA, 2011.

<sup>41</sup> Ibid.

<sup>42</sup> M. Bando et al., “Dynamical Model of Traffic Congestion and Numerical Simulation,” *Physical Review E* 51, no. 2 (February 1995): 1036–042.

<sup>43</sup> Erik T. Verhoef, “Time, Speeds, Flows and Densities in Static Models of Road Traffic Congestion and Congestion Pricing,” *Regional Science and Urban Economics* 29, no. 3 (1999): 341–69.

conditions, traffic flow, and peak-hour travel, Ma, Huang, and Jiang's model mathematically proves these theories.<sup>44</sup>

### C. AUTONOMOUS VEHICLE EFFICIENCY

Fernandes and Nunes present very pertinent information in their 2012 journal article regarding intervehicle communications.<sup>45</sup> Although the bulk of the report concerns algorithms needed for efficient interaction between autonomous vehicles within a platoon, they present very good equations to determine a “desired minimum gap” between vehicles and an equation for calculating road capacity, a concept central to the question of this thesis. The equation is as follows:

$$C = v \frac{n}{ns + (n - 1)d + D}$$

where

C = number of vehicles (in vehicles per second)

d = intraplatoon spacing

D = interplatoon spacing

S = vehicle length (in meters)

V = steady-state speed (in meters per second)

N = number of vehicles in each platoon

For this thesis, manipulation of this equation will provide a baseline for the adoption rate of autonomous vehicles needed to prevent road networks from becoming unusable.

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<sup>44</sup> Jiming Ma, Huang Xianfang, and Jiang Yaping, “Congestion Based on Rough Set Theory and Genetic Algorithm” (master's thesis, Zhengzhou University of Light Industry, n.d.).

<sup>45</sup> Pedro Fernandes and Urbano Nunes, “Platooning With IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow,” *IEEE Transactions on Intelligent Transportation Systems* 13, no. 1 (2012): 91–106.

The U.S. Department of Transportation (DOT) released a policy to guide the development of driverless vehicles, which describes federal requirements applied to automotive manufacturers.<sup>46</sup> The DOT document provides detailed provisions for vehicle safety testing and test waiver procedures, but does not address any standardization conditions regarding vehicle production.<sup>47</sup> Cyber security concerns receive a small mention in the document and while the DOT provides some vague suggestions on the topic, specific guidance, or requirements are absent.<sup>48</sup>

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<sup>46</sup> “Federal Automated Vehicles Policy: Accelerating the Next Revolution in Roadway Safety,” accessed September 27, 2016, <https://www.transportation.gov/sites/dot.gov/files/docs/AV%20policy%20guidance%20PDF.pdf>.

<sup>47</sup> Ibid.

<sup>48</sup> Ibid.

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### III. CONGESTION MODELLING

Traffic congestion is a growing problem in the United States and a potential threat to homeland security. First, to quantify the impact of congestion, the projected population increase in America, and the impact that may have on traffic congestions were investigated. Then, with a series of mathematical models, indicate the traffic reduction potential of autonomous vehicles.

A National Research Council workshop estimated that highway congestion costs Americans approximately \$65 billion per year (2005 dollars) through the loss of productivity and manpower while waiting in traffic.<sup>49</sup> In addition, 2.3 billion gallons of fuel are wasted in roadway congestion, both costing resources and needlessly affecting the environment.<sup>50</sup> Dividing population projection data from the U.S. Census Department by the number of registered vehicles reported on Statista.com yielded a ratio. Based on historical data, an 80% vehicle-to-population ratio was created and applied to Census Department population predictions. The results are captured in Table 1.

Table 1. Number of Registered Vehicles in the United States.

	<b>Population</b> <sup>51</sup>	<b>Registered Vehicles</b> <sup>52</sup>	<b>Ratio Vehicle/Pop</b>
1994	261,431,000	201,801,920	77%
2004	293,655,404	243,010,550	82%
2014	318,857,056	260,350,940	81%
2024	344,814,000	275,851,200*	80%*
2034	368,246,000	294,596,800*	80%*
2044	387,593,000	310,074,400*	80%*
2054	405,572,000	324,457,600*	80%*

\*Interpolated data

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<sup>49</sup> Nash et al., “Sustainable Critical Infrastructure Systems,” 17.

<sup>50</sup> Ibid.

<sup>51</sup> “2014 National Population Projections: Summary Table,” December 2014, <http://www.census.gov/population/projections/data/national/2014/summarytables.html>.

<sup>52</sup> “Statistics and Facts about the U.S. Automotive Industry: New Car Registrations December 2015 YTD,” December 2015, <https://www.statista.com/statistics/269872/largest-automobile-markets-worldwide-based-on-new-car-registrations/>.

In the next 30 years, the United States may see as many as 50 million additional vehicles on the roadways, which would approximately amount to a 20% increase. Since 85% of the population resides in urban areas, the majority of those vehicles will be added to the already congested metropolitan area roadways.<sup>53</sup>

To understand the how the number of vehicles on a roadway can impact traffic flow, a simple model will be used to illustrate how human-driven vehicles interact in congested conditions. For simplicity, a single lane of vehicles will be considered, traveling at some velocity  $V(t)$ . Vehicles must maintain safe spacing in that line. Many traffic safety websites suggest a three-second interval between vehicles.<sup>54</sup> Generalizing by using  $t_s$  to represent the spacing time yields the following equation:

$$S = t_s * V(t)$$

This equation fits a reasonability test because as speed increases, vehicle spacing will also increase. In addition to the spacing between vehicles, each conveyance occupies a section of roadway itself, which will be defined as  $l_c$ . This number can be added to the spacing equation to create a rudimentary static linear density equation:

$$\rho = l_c + S$$

Linear density was then calculated by using a vehicle length of 5 meters and varying the velocity of the vehicles. Table 2 illustrates that the linear density of vehicles diminishes as the velocity increases, which is a logical conclusion based on the equation because as speed increases, safe following distance must increase to allow for human reaction time.

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<sup>53</sup> U.S. Department of Homeland Security, *2014 Quadrennial Homeland Security Review*.

<sup>54</sup> “Maintain a Safe Following Distance (The 3 Second Rule),” accessed September 22, 2016, <http://www.smartmotorist.com/traffic-and-safety-guideline/maintain-a-safe-following-distance-the-3-second-rule.html>.

Table 2. Static Linear Density for Human Driven Vehicles.

<b>V</b> Kilometers per hour	<b>S</b> Meters	<b>ρ</b> Static Linear Density
36	35	29
40	38.333	26
56	51.667	19
72	65	15
88	78.333	13
104	91.667	11
112	98.333	10

Static linear density provides a baseline to compute the number of vehicles that can pass through a given area over a period of time. By multiplying the static density by the velocity of the vehicles, a thru-put capacity for a lane kilometer of roadway can be developed as shown in Table 3.

Table 3. Vehicles per Lane Kilometer per Hour.

<b>V</b> Kilometers per hour	<b>ρ</b> Static Linear Density	Vehicles per lane kilometer per hour
36	29	1029
40	26	1043
56	19	1084
72	15	1108
88	13	1123
104	11	1135
112	10	1139

Since vehicle spacing increases as speed increases, only a minimal increase can occur in thru-put per lane kilometer per hour. Despite the simplicity of this model, it demonstrates a fairly static carrying capacity for a roadway system in any given area. In reality, this capacity would be further diminished by any number of perturbations to the system. The disruptions can include weather, lane closures, merging traffic, and accidents among others. For the sake of comparison, the traffic pattern disruption has been set aside

with the acknowledgment that actual lane kilometer thru-put would be less than calculated.

Autonomous control systems in vehicles facilitate the reduction of the safe driving distance between vehicles. Since 2014, Peleton Technologies has promoted after-market technology designed to link freight trucks together to form two-vehicle platoons.<sup>55</sup> Sensors and computer controls allow the two vehicles to travel safely more closely together. This technology, marketed for the fuel savings it provides to both trucks in the platoon,<sup>56</sup> also allows for maintaining a smaller distance between vehicles even at higher speeds. Similar technology is in development for use in passenger vehicles. Reduced and standardized spacing between vehicles in a platoon would yield a far greater thru-put for roadways. Fernandes and Nunes' equation for vehicle spacing and road capacity of autonomous vehicles platooning together follows:<sup>57</sup>

$$C = v \frac{n}{ns + (n - 1)d + D}$$

where

C = number of vehicles (in vehicles per second)

d = intraplatoon spacing

D = interplatoon spacing

s = vehicle length (in meters)

v = steady-state speed (in meters per second)

n = number of vehicles in each platoon

With only the numerator used to generate a static linear capacity for a single car platoon, numbers similar to the human drive car equation were generated. After proving these equations are comparable, a portion of the Fernandes–Nunes equation,

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<sup>55</sup> Cassandra Khaw, "Computer-assisted Trucks Could Be on Nevada Roads by Next Year," The Verge, June 3, 2014, <http://www.theverge.com/2014/6/3/5774952/automated-trucks-nevada>.

<sup>56</sup> "Safety and Efficiency: Truck Platooning," accessed September 22, 2016, <http://peloton-tech.com/>.

<sup>57</sup> Fernandes and Nunes, "Platooning with IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow," 91–106.



$$ns + (n - 1)d + D,$$

was used again to calculate static linear capacity at various velocities, but with five-vehicle and 10-vehicle platoons. The assumption of a five-meter vehicle length was maintained, and a set distance of two meters between vehicles in the platoon was created. A platoon of vehicles would maintain the same three-second interval between it and the next platoon. The final assumption is that only platoons of vehicles would travel on a given lane of roadway. Table 4 provides the findings.

Table 4. Static Linear Density Including Autonomous Vehicles.

<b>V</b> Kilometers per hour	<b>ρ</b> Static Linear Density (Human driver)	<b>ρ</b> Static Linear Density (5 Vehicle Platoon)	<b>ρ</b> Static Linear Density (10 Vehicle Platoon)
36	29	79	102
40	26	75	99
56	19	63	87
72	15	54	78
88	13	47	71
104	11	42	65
112	10	40	62

A significant increase in static density is readily apparent with autonomous systems controlling the spacing in between vehicles. This increase in road use efficiency becomes more apparent when placed in the thru-put model as shown in Table 5 and Figure 1.

Table 5. Vehicles per Lane Kilometer per Hour Including Autonomous Vehicles.

V Kilometers per hour	Vehicle per lane km/h Human driver	Vehicle per lane km/h 5-Vehicle Platoon	Vehicle per lane km/h 10-Vehicle Platoon
36	1029	2857	3673
40	1043	3015	3947
56	1084	3515	4884
72	1108	3871	5625
88	1123	4138	6226
104	1135	4345	6724
112	1139	4433	6942

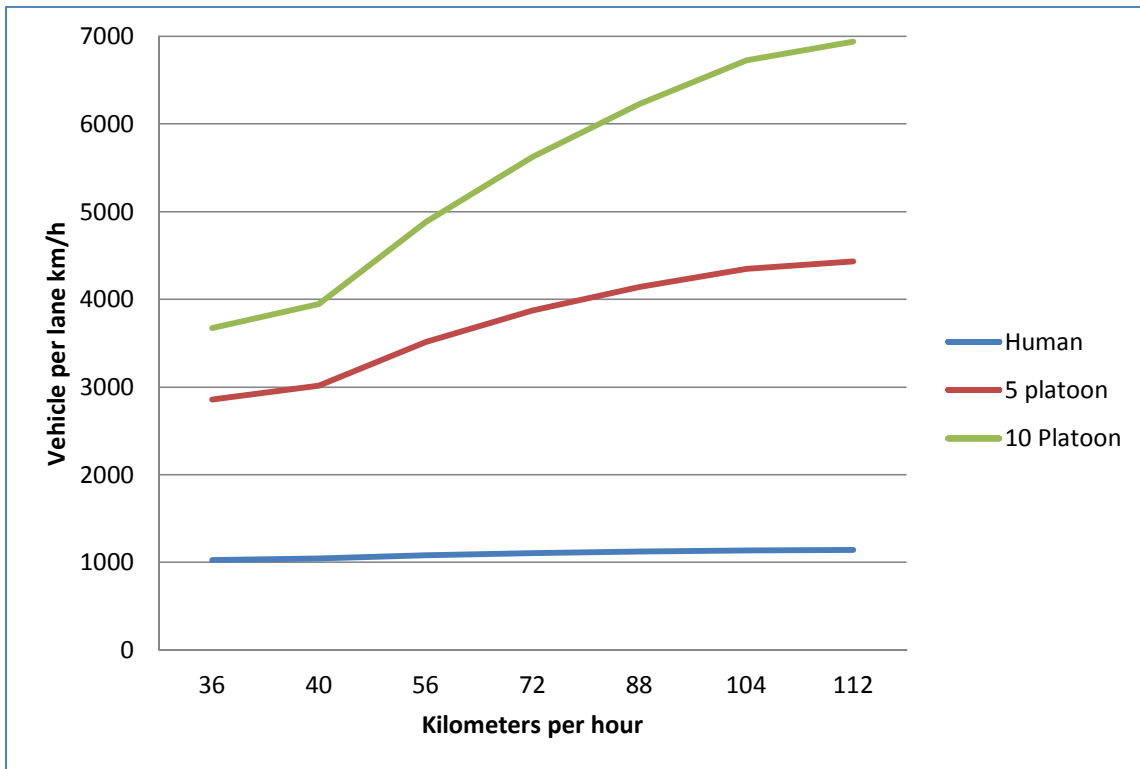


Figure 1. Lane Thru-Put.

Figure 1 clearly indicates that despite the relatively static nature of the carrying capacity of a roadway for human-driven vehicles, autonomous platooning greatly increases the dynamic thru-put of a given lane kilometer. At 88 kilometers per hour

(approximately 55 miles per hour), five-vehicle platoons would yield an approximate 350% increase in the road carrying capacity; and 10-vehicle platoons would increase capacity by almost 550%. Again, these numbers are based on simplified models of vehicle traffic. Vehicles of different sizes, such as freight-hauling trucks, would reduce these gained efficiencies, leading to smaller capacity increases. Regardless of the limitations of this simple model, it proves that the use of autonomous vehicles can dramatically increase the carrying capacity of the U.S. road network. Earlier in this chapter, extrapolation of census and vehicle registration data predicted a 20% increase in the number of vehicles on American roadways. If even modest capacity gains can be made by the use of autonomous vehicles, roadways can accommodate this increase in traffic.

Population increases and additional vehicles are not the only factors that need to be addressed. As noted above, current traffic congestion costs the United States billions of dollars per year in lost productivity.<sup>58</sup> The adoption rate of autonomous vehicles needs not only to keep pace with the addition of more vehicles into the system in the future but also alleviate congestion issues that already plague urban areas. Existing congestion was described in great detail in 1962 by Anthony Downs,<sup>59</sup> who created “The Law of Peak-Hour Expressway Congestion,” which has become fundamental to many studies of traffic and congestion.<sup>60</sup> Downs theorizes that peak-hour congestion will rise to meet maximum capacity.<sup>61</sup> This theory was further synthesized by Canadian economists Duranton and Turner when they studied U.S. cities and determined that if roadway capacities (supply) were increased, use of those roadways (demand) would increase to match.<sup>62</sup> Extrapolating, they found that by making travel easier, thus reducing the cost of travel,

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<sup>58</sup> Nash et al., “Sustainable Critical Infrastructure Systems,” 17.

<sup>59</sup> Anthony Downs, “The Law of Peak-Hour Expressway Congestion,” *Traffic Quarterly* 16, no. 3 (1962): 393–409.

<sup>60</sup> Ibid.

<sup>61</sup> Ibid.

<sup>62</sup> Gilles Duranton and Matthew A. Turner, *The Fundamental Law of Road Congestion: Evidence from U.S. Cities* (Cambridge, MA: National Bureau of Economic Research, 2009).

commuters would be willing to make more trips.<sup>63</sup> They proved that increases in capacity resulted in more vehicle kilometers traveled and concluded that changes in individual behavior are the way to reduce congestion. These behaviors were described by Bando et al. in their 1995 dynamic modelling paper in which they further investigated the causes of traffic congestion. They based their research not on the safe following distance model but on the ability of vehicles to maintain legal speed.<sup>64</sup> As a preceding vehicle decreases speed, all following vehicles must decrease speed to maintain separation and avoid collisions.<sup>65</sup> Doing so would net a similar outcome of maintaining a certain headway distance, but the equations were focused on the variation of velocity. Their research includes a Fourier series analysis of their equation that concludes that even very small changes in the system cause instability in the “steady state flow,” which leads to congestion.<sup>66</sup> Their conclusion follows a logical analysis and is demonstrated by their numbers. Responses to changes in the system are delayed as a result of human reaction time and amplified as they move back through the flow of traffic.<sup>67</sup> In dense traffic flow, this amplification can bring traffic to a standstill in the absence of any accidents, weather conditions, or lane reductions.

Autonomous cooperative vehicles provide an opportunity to change this human behavior. Autonomous features like cruise control have been available in passenger cars since the late 1950s, but once the technology allows vehicles to communicate and cooperate, changes in driving behavior can cause major effects on congestion.<sup>68</sup> Vehicle-to-vehicle and vehicle-to-infrastructure communications will allow not only for the platooning of vehicles but also an optimization of the traffic patterns on an entire

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<sup>63</sup> Ibid.

<sup>64</sup> Bando et al., “Dynamical Model of Traffic Congestion and Numerical Simulation,” 1036–042.

<sup>65</sup> Bando et al., “Dynamical Model of Traffic Congestion and Numerical Simulation,” 1036–042.

<sup>66</sup> Ibid.

<sup>67</sup> Ibid.

<sup>68</sup> “1958 Chrysler Auto Pilot Brochure,” accessed September 22, 2016, [http://www.oldcarbrochures.com/static/NA/Chrysler\\_and\\_Imperial/1958\\_Chrysler/1958\\_Chrysler\\_Auto-Pilot\\_Brochure/1958%20Chrysler%20Auto-Pilot%20Brochure-01.html](http://www.oldcarbrochures.com/static/NA/Chrysler_and_Imperial/1958_Chrysler/1958_Chrysler_Auto-Pilot_Brochure/1958%20Chrysler%20Auto-Pilot%20Brochure-01.html).

roadway.<sup>69</sup> Completely autonomous vehicles will be programed with their final destination information. Once they connect to the network of vehicles, they will be able to form platoons of conveyances heading to similar areas for efficiency. Vehicles will allow other vehicles to merge and exit the traffic flow without disrupting the overall system. The small perturbations caused by human reaction time that are amplified over current traffic patterns could be significantly reduced. Human reactions are based on visual observations of only a few vehicles directly ahead, but an autonomous network could alert all vehicles to variations miles ahead, allowing for a correction in the entire system, which could smooth perturbations instead of amplify them. For this coordinated system of autonomous vehicles to function, a significant adoption rate is needed. The next chapter includes a discussion of the factors involved with the adoption rate, options available to policy makers, and potential resistance to autonomous adoption.

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<sup>69</sup> Diakaki et al., *Overview and Analysis of Vehicle Automation and Communication Systems from a Motorway Traffic Management Perspective*, *Traffic Management for the 21st Century*.

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## IV. POLICY ANALYSIS

Since the adoption of coordinated autonomous vehicle technology is critical to relieving congestion and increasing roadway capacity, certain factors must be considered to maximize the congestion-relieving benefits of the emergent technology. The first is that the vehicles are fully autonomous. Many safety innovations have been incorporated into current vehicles, such as intelligent cruise control, blind-spot warning, and lane keeping. For the 2022 model year, major auto manufacturers have indicated that automatic braking will be a standard safety feature on all vehicles;<sup>70</sup> however, these systems will still rely on human piloting for a majority of vehicle control, resulting in inconsistencies in human behavior and human reaction time that can be eliminated only through autonomous systems. The second factor is that the vehicles will be able to communicate to create a coordinated system. A high adoption rate will allow fluctuations within the system to be minimized and distributed across many vehicles instead of amplified as they ripple through the traffic flow. Achieving the needed adoption rate may necessitate facilitation by policy makers at local, state, and federal levels. Three policy options will be investigated in this chapter: first, positive incentives, some through government subsidies; second, negative incentives through restrictions and penalties; and third, government allowance of market facilitation of autonomous adoption perhaps with some regulation.

### A. POSITIVE INCENTIVES

To ensure the adoption of autonomous vehicle technology at the rates needed, encouragement may be necessary through a method like a government subsidy program. Vehicle purchase subsidies have been used in the United States before. In 2009, the government implemented the Car Allowance Rebate System (CARS),<sup>71</sup> or Cash for

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<sup>70</sup> Bill Chappell, “Automatic Braking Systems To Become Standard On Most U.S. Vehicles,” *The Two-way: Breaking News from NPR*, March 17, 2016, <http://www.npr.org/sections/thetwo-way/2016/03/17/470809148/automatic-braking-systems-to-become-standard-on-most-u-s-vehicles>.

<sup>71</sup> Ted Gayer and Emily Parker, *Cash for Clunkers: An Evaluation of the Car Allowance Rebate System* (Washington, DC: Brookings Institute 2013), [http://www.brookings.edu/~media/research/files/papers/2013/10/cash-for-clunkers-evaluation-gayer/cash\\_for\\_clunkers\\_evaluation\\_paper\\_gayer.pdf](http://www.brookings.edu/~media/research/files/papers/2013/10/cash-for-clunkers-evaluation-gayer/cash_for_clunkers_evaluation_paper_gayer.pdf).

Clunkers, intended both to remove low fuel efficiency vehicles from the road, as well as to stimulate the nation's economy.<sup>72</sup> The program had a number of requirements but provided a voucher worth up to \$4,500 toward the purchase of a new car with a qualifying trade in.<sup>73</sup> Inefficient vehicles were rendered inoperable and sold for scrap.<sup>74</sup> The program extended from July 2009 until November 2009,<sup>75</sup> during which time 677,842 new vehicles were reported to have been purchased, and \$2.85 billion in vouchers were redeemed.<sup>76</sup> Fifteen percent more vehicles were purchased than expected during those months. A mixed success, Cash for Clunkers removed nearly 700,000 inefficient vehicles from circulation; however, a study at Texas A&M showed that the economic stimulus fell short. Researchers concluded that although many new cars were purchased, the fuel efficiency requirements of the program encouraged consumers to purchase cars less expensive than they would normally buy,<sup>77</sup> producing a net effect of approximately \$3 billion less in automobile spending.

Even with the mixed results, the Car Allowance Rebate Act provides a model for the structure of a government subsidy to encourage the adoption of autonomous vehicles. Similar to Cash for Clunkers, vouchers could be issued for qualifying trade-in vehicles when purchasing an autonomous vehicle. The voucher system would be helpful in offsetting the additional expense for the extra equipment required in an autonomous vehicle. The size of the subsidy would be based on the cost of the additional equipment, which has dramatically decreased in price over time. Current self-driving vehicle prototypes have used Laser Detection and Ranging (LIDAR) technology in their sensor packages.<sup>78</sup> In 2014, these systems cost approximately \$75,000 per vehicle,<sup>79</sup> but

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<sup>72</sup> Gayer and Parker, *Cash for Clunkers: An Evaluation of the Car Allowance Rebate System*.

<sup>73</sup> Ibid.

<sup>74</sup> Ibid.

<sup>75</sup> Ibid.

<sup>76</sup> Ibid.

<sup>77</sup> Mark Hoekstra, Steven L. Puller, and Jeremy West, *Cash for Corollas: When Stimulus Reduces Spending* (College Station, TX: Texas A&M, 2015).

<sup>78</sup> Chris Neiger, "How Much Do Driverless Cars Cost?" *The Motley Fool*, August 4, 2016, <http://www.fool.com/investing/2016/08/04/how-much-do-driverless-cars-cost.aspx>.

<sup>79</sup> Ibid.



Velodyne, a company that manufactures LIDAR hardware, has created a smaller but still capable unit for \$500. The company sent its first shipment to the Ford Motor Company in early 2016. Other components are needed to create a full autonomous vehicle, but this example shows that the cost of the extra equipment is decreasing.

An additional incentive available to owners of autonomous vehicles is flexible speed limits. Vehicle-to-infrastructure communication would allow for the safe speed of a platoon of autonomous vehicles to increase or decrease depending on road conditions. In times of clear weather and moderate traffic flow, the technology would allow those vehicles to travel faster while maintaining margins of safety; for example, posted limits for human-driven cars could be 65 miles per hour, but autonomous vehicles could travel at 85 miles per hour.

## **B. NEGATIVE INCENTIVE**

Another option useful to encourage the adoption of autonomous vehicle technology is a penalty imposed upon those failing to use the technology. A negative incentive would be levied on motorists using something other than an autonomous vehicle. Much like the subsidy program, this concept is nothing new in the ground-based transportation segment. A method of combating congestion in metropolitan areas in the past has included the use of high-occupancy vehicle lanes.<sup>80</sup> To encourage carpooling as a way to minimize the number of vehicles on the roadway, lanes were reserved for vehicles carrying more than one person and in some cases, more than two people. Municipalities could easily redesignate sections of roadways for use by autonomous vehicles only. Over time, the number of lanes that would permit the use of nonautonomous vehicles could shrink to one or perhaps none, requiring drivers who have not adopted the new technology to seek alternate routes. Although doing so may seem like a harsh measure, precedents exist. Interstate highways have a minimum speed requirement that must be met to use those facilities; in fact, owners of historic vehicles that do not meet these requirements cannot drive them on the interstate. Municipalities

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<sup>80</sup> “High-Occupancy Vehicle Lanes,” modified October 26, 2015, <https://www.transportation.gov/mission/health/High-Occupancy-Vehicle-Lanes>.

could have a phased approach to lane usage for autonomous vehicles, leading to some roads deemed off limits to human drivers.

Congestion pricing, also a very common practice in areas of high traffic volume, involves a system that modulates the toll pricing on roadways to match the current volumes of traffic. The idea is to disincentivize the use of these roadways by discretionary drivers during times of greater demand.<sup>81</sup> The system operates under the assumption that a portion of the drivers on the urban roadways during rush hour periods does not comprise commuters, and the pricing will encourage them to travel at nonpeak times.<sup>82</sup> Congestion pricing has four typical implementation strategies: variably priced lanes, variable tolls on entire roadways, cordon charges (to enter certain parts of an urban area) and area-wide charges.<sup>83</sup> With variably priced lanes, which operate like high-occupancy vehicle lanes, tolling is limited to a portion of the roadway; lanes are referred to as express toll lanes or high-occupancy tolling (HOT).<sup>84</sup> In some places, high-occupancy vehicles may travel on these roadways without paying the tolling charges or paying a reduced rate while low-occupancy vehicles may use the lanes at a price.<sup>85</sup> This strategy would not be the most effective with autonomous vehicles because they will perform at a great capacity (platooning) when they are segregated from human-driven vehicles. Cordon charges, which involve a strategy more effective for autonomous vehicle adoption for surface streets in urban areas, are tolls applied to all vehicles entering certain areas; they can vary based on congestion.<sup>86</sup> The layouts of many urban and metropolitan area roadways preclude the segregation of certain lanes in downtown areas. After autonomous vehicles leave the highway setting, cordon charges during peak periods for nonautonomous vehicles could reduce the number of discretionary drivers in downtown areas, as well as encourage the adoption of the new technology.

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<sup>81</sup> “What is Congestion Pricing?” modified July 31, 2014, <http://ops.fhwa.dot.gov/publications/congestionpricing/sec2.htm>.

<sup>82</sup> Ibid.

<sup>83</sup> Ibid.

<sup>84</sup> Ibid.

<sup>85</sup> Ibid.

<sup>86</sup> Ibid.

### C. MARKET DRIVEN CHANGE

Automobile manufacturers have incorporated increasing numbers of technological features into vehicles with each model year, including the vehicle automation and communication systems described previously.<sup>87</sup> A strong possibility exists that the adoptions of autonomous vehicle technology will occur without the need for government incentives. Semiautonomous vehicle packages already available from Honda and Tesla<sup>88</sup> still require some human interaction to travel from one destination to another but have the ability to maintain vehicle spacing, steering, acceleration, and braking while traveling on highways.<sup>89</sup> IHS Automotive has predicted that by the year 2035, the complete hardware package needed to create a fully autonomous vehicle will cost approximately \$3,000;<sup>90</sup> furthermore, by 2035 at least 10% of all vehicles in the United States will be fully automated, and by 2050, the majority of traffic on roadways will require no human input.<sup>91</sup> The development of this technology has accelerated almost daily as a result of market forces. Ford Motor and the ride-sharing company Uber have announced a joint venture to launch a fleet of driverless Ford Fusions to be used as autonomous taxis in Pittsburgh, PA.<sup>92</sup> Free test rides have already been offered to loyal Uber customers.<sup>93</sup> Electric vehicle innovator Tesla has incorporated urban transportation options and autonomous ride-hailing services into its Master Plan,<sup>94</sup> and technology giant Apple has

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<sup>87</sup> Diakaki et al., *Overview and Analysis of Vehicle Automation and Communication Systems from a Motorway Traffic Management Perspective*, *Traffic Management for the 21st Century*.

<sup>88</sup> Chris Neiger, "How Much Do Driverless Cars Cost?"

<sup>89</sup> Ibid.

<sup>90</sup> Ibid.

<sup>91</sup> Ibid.

<sup>92</sup> Danielle Muoio, "We Rode in Uber's Self-driving Car—Here's What it Was Like," *Business Insider*, September 14, 2014, <http://www.businessinsider.com/uber-driverless-car-in-pittsburgh-review-photos-2016-9/>.

<sup>93</sup> Ibid.

<sup>94</sup> Daniel Sparks, "Tesla's New Master Plan: Everything You Need to Know about Elon Musk's Wild, Futuristic Vision," *The Motley Fool*, July 21, 2016, <http://www.fool.com/investing/2016/07/21/teslas-new-master-plan-everything-you-need-to-know.aspx>.

spent over \$5 billion on automotive research and development<sup>95</sup> for “Project Titan,” designed to offer autonomous cars as a service instead of selling them as a commodity to consumers.<sup>96</sup> Insurance coverage for autonomous vehicles will be another major factor in the free market economy. Some estimates indicate that insurance premiums for autonomous vehicles may drop 20% in the next 20 years and continue to drop as adoption increases.<sup>97</sup> Higher premiums on human-driven vehicles may also encourage the implementation of the technology.

Although these developments may eliminate the need for government incentives to encourage the adoption of autonomous vehicle technology, government coordination and regulation will still represent a significant need. Any adoption strategy will require standardization of the way in which vehicle control systems interface with one another to create a transportation grid. Incompatible operating systems would disallow the efficiencies created by vehicle-to-vehicle communication and may even lead to dangerous situations on the roadways. Like other communications networks, the signal frequencies will at minimum fall under the regulatory authority of the Federal Communication Commission.<sup>98</sup> Policy makers must be proactive in creating this standardization but minimize interference with the innovation of emergent technology. Once adoption rates increase, segregating nonautonomous vehicles from driverless vehicles may be necessary. As noted previously, such segregation could encourage autonomous adoption, but it may still be needed for safety and efficiency, regardless of how the technology is adopted. The behaviors of autonomous and human-piloted vehicles are different enough that they warrant segregation.

Autonomous vehicles will be controlled by program algorithms. When situations involving accident avoidance arise, these algorithms will be used to determine the safest

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<sup>95</sup> Chris Neiger, “Apple Inc. Increased R&D Spending Faster Than the Top 14 Automakers Combined —Here’s Why,” *The Motley Fool*, June 1, 2016, <http://www.fool.com/investing/2016/06/01/apple-inc-increased-rd-spending-faster-than-the-to.aspx>.

<sup>96</sup> Ibid.

<sup>97</sup> “Driverless Cars to Slash U.S. Auto Insurance Premiums,” September 21, 2016, <http://www.insurancejournal.com/news/national/2016/09/12/425980.htm>.

<sup>98</sup> Telecommunications, 47 C.F.R. (2016).

course of action. With a human driver, split-second decisions are often near involuntary reactions; however, when an algorithm is created for reaction in certain scenarios, the possibility of ethical issues comes into play.<sup>99</sup> If the vehicle is in a situation involving the choice between hitting an obstruction in the road that may injure its passengers or aggressively changing lanes and striking another vehicle, which choice will result from the application of the algorithm? What if the other vehicle is a motorcycle, and the vehicle occupants would have a low probability of injury; but the motorcyclist would have a high probability of mortality? When human drivers react, they do not have time to consider all these factors, but a programmer, sitting safely behind a keyboard, will create valuations that will drive the algorithms and the favorability of one alternative over the other. Some experts have dismissed this claim, stating that the probability of these scenarios is so remote that they merit no investigation;<sup>100</sup> but even if that is the case, the perception is that algorithms are somehow undergirded by ethics.<sup>101</sup> A survey by *Science* magazine presented to a group of participants precisely this ethical dilemma with regard to autonomous vehicles.<sup>102</sup> Given a scenario that the surveyed person was the only passenger in the car, the majority of respondents believed that an algorithm based on altruism would save the most people and was the most favored.<sup>103</sup> When the question was changed to include the respondents' loved ones in the car with them, a sharp change favored an algorithm that resulted in the protection of the vehicle passengers at all costs.<sup>104</sup> These ethical dilemmas may or may not present themselves, but consumer perception of the possibility figures strongly in decision making. One vehicle manufacturer could try to increase demand from a certain population segment by advertising that the company uses one type of algorithm over another. That sort of consumer manipulation creates a situation that would benefit from further investigation

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<sup>99</sup> Jean-François Bonnefon, Azim Shariff, and Iyad Rahwan, "The Social Dilemma of Autonomous Vehicles," *Science Magazine*, June 24, 2016, 1573–6.

<sup>100</sup> Lee, "Driverless Car Ethics: When 'Gut Decisions' Are Made By Machines," Safety Resource Center, September 20, 2016, <https://www.trafficsafetystore.com/blog/driverless-car-ethics/>

<sup>101</sup> Bonnefon, Shariff, and Rahwan, "The Social Dilemma of Autonomous Vehicles."

<sup>102</sup> Ibid.

<sup>103</sup> Ibid.

<sup>104</sup> Ibid.

by policy makers. The full scope of this ethical debate will not be addressed in this thesis but remains a topic for future research.

Policy makers must consider some additional factors. The first concerns the motor fuel use taxes placed on all domestic gasoline and diesel sales.<sup>105</sup> Approximately 10 cents of every dollar of fuel sold serves as a tax placed into a highway account and used for maintenance and construction,<sup>106</sup> but if autonomous vehicles constitute a more fuel efficient fleet, the funding that maintains the roadways they travel may be reduced. Fuel efficiency is good for the larger economy of America and very beneficial to the environment, but government leaders at all levels will need to be prepared for roadway maintenance budget decreases.

Another potential change will occur when people perceive the ownership of vehicles in a different way. The sharing economy in the United States has increased considerably in recent years. In many urban areas, individuals have foregone purchasing vehicles and have instead joined car-sharing programs like Zipcar, a short-term car rental program in which participants pay either a one-time or a monthly fee and can subsequently use cars located in parking lots throughout the metropolitan area.<sup>107</sup> Car sharing has expanded to include bike-sharing programs like Capital Bikeshare in Washington, DC.<sup>108</sup> Simultaneously, the millennial generation has eschewed ownership of modes of transportation, and technology has facilitated the entrance of the phenomenon of sharing to enter into the service industry. Dedicated taxicab services have been supplanted by companies like Uber and Lyft, in which the owners of personal vehicles provide rides for a fee.<sup>109</sup> The traditional hotel business model has also been affected by entities like Airbnb, in which private homes or rooms in homes are rented on

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<sup>105</sup> “Motor Fuel Tax Compliance Outreach,” accessed September 22, 2016 <http://www.fhwa.dot.gov/motorfuel/faqs.htm#q1>.

<sup>106</sup> Ibid.

<sup>107</sup> “How to Zip,” accessed September 22, 2016, <http://www.zipcar.com/how>.

<sup>108</sup> “What is Capital Bikeshare?” accessed September 22, 2016, <http://www.capitalbikeshare.com/>.

<sup>109</sup> “Always the Ride You Want,” accessed September 22, 2016, <https://www.uber.com/ride/>; “Rides in Minutes,” accessed September 22, 2016, <https://www.lyft.com/>.

a short-term basis.<sup>110</sup> If future generations continue to embrace and expand the philosophy of sharing, the total number of vehicles in urban areas may decrease. Autonomous vehicles could also enhance ride-sharing and car-sharing services, in which a user could request a vehicle via a mobile device to drive directly to the consumer's location. Such a scenario appeared in the movie *Hot Tub Time Machine 2*,<sup>111</sup> which depicted a future in which no one owed a car and autonomous vehicles were viewed as a service instead of a possession, hardly a simple Hollywood fantasy. Google engineers have designed self-driving "pods" devoid of any pedals, levers, or steering wheels unlike standard automobiles.<sup>112</sup> In addition, a lobbying organization called Self-Driving Coalition for Safer Streets, was created in a partnership involving Ford, Volvo, Lyft, Uber, and Google,<sup>113</sup> powerful companies attempting to influence public policy. Relating statistics that 94% of fatal automotive accidents are the result of human error,<sup>114</sup> the coalition supports the elimination of the human component to make roads safer. Supporting the argument for the vehicle as a possession, however, is the strong connection between owners and vehicles. The open road and the freedom to travel are iconic in American popular culture, producers of movies, television, and music romanticizing the images of a vehicle (a car, a truck, or a motorcycle) and its owner; furthermore, a multitude of social clubs center on vehicle ownership. Policy makers must balance the need for safety and efficiency with the emotions that some have for their vehicles. Some may even suggest completely removing humans from the driver's seat in the interest of public safety, leaving many red barchettas hidden away in garages and barns all over the country.<sup>115</sup>

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<sup>110</sup> "How It Works," accessed September 22, 2016, <https://www.airbnb.com/help/getting-started/how-it-works>.

<sup>111</sup> Josh Heald, *Hot Tub Time Machine 2*, directed by Steve Pink (Los Angeles, CA: Paramount Pictures, 2015).

<sup>112</sup> John Naughton, "Will Google's Self-driving Pods Spell the End of the Road for Car Ownership?" *The Guardian*, May 31, 2014, <https://www.theguardian.com/technology/2014/jun/01/google-self-driving-pods-end-of-road-car-ownership>.

<sup>113</sup> "The Self-driving Coalition for Safer Streets," accessed September 22, 2016, <http://www.self-drivingcoalition.org/>.

<sup>114</sup> Ibid.

<sup>115</sup> Rush, "Red Barchetta," by Neil Peart, Geddy Lee, and Alex Lifeson, recorded October–November 1980, on *Moving Pictures*, Mercury, 33 1/3 rpm.

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## **V. RECOMMENDATIONS**

The data in Chapter III has demonstrated that a significant roadway capacity increase will be achieved through the platooning of autonomous vehicles, which has been independently verified in other scholarly journals. The economic and environmental benefits to this increased capacity far outweigh the expense of the technology. Chapter IV investigated options policy makers could take to affect the adoption rate of this emergent technology. Those options included government subsidies, government restrictions on non-autonomous vehicles, and allowing the free market to encourage adoption with appropriate government regulation. This paper recommends that policy makers engage in the third option. Decreases in the cost of hardware, coupled with the increase in interest coming from both automotive and technology sectors, will propel this innovation forward. Lobbyist coalitions have made it clear that the industry is serious about both the technology and the ability to influence lawmakers. The appropriate level of engagement for federal, state, and local officials will be one of regulation. Ensuring safety standards will be very important. Adjusting roadway usage, such as designated autonomous lanes, will increase efficiency and safety as the saturation of autonomous vehicles increase in the overall fleet. Assigning communications frequencies and ensuring compatibility of operating systems will still be necessary. Finally, adjusting state and local vehicle laws to allow for driverless vehicles will be needed to make way for a shift to an autonomous future. This technology is evolving daily. As new innovations and new information are emerging very rapidly, policy makers must be proactive so that they can keep up. Without maintaining the same inertia as innovation, policies and regulations may become obsolete in the time between creating and enacting.

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